COMMERCIAL DEVELOPMENT OF ADVANCED PFBC TECHNOLOGY

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INTRODUCTION

In the 1970s, the coal-fired power generation industry recognized that the declining price of electricity over the previous five decades was coming to an end. Maximum use had been made of existing cycle efficiencies and scale-up. As researchers looked for a new approach, the focus shifted from the fully developed Rankine cycle to a new array of coal-fired plants using combined-cycle technology. Now, coal-fired combined-cycle plants are being introduced that shift power production to the Brayton cycle. Integrated Gasification Combined Cycle (IGCC) and Pressurized Fluidized Bed Combustion (PFBC) are two technologies at the forefront of this approach.

The PFBC approach burns coal in a fluidized bed combustor at elevated pressure. The plant generates electricity from a gas turbine (expanding the hot, pressurized products of combustion) in addition to the conventional steam (bottoming) cycle. Such a plant can achieve thermal efficiencies of about 40 percent and have a levelized busbar cost below any competing coal-based technology. In addition to the economic benefits, the "built-in" feature of environmental control (SO_2 and NO_x) in the combustion process eliminates the need for external gas cleanup such as scrubbers. A PFBC can burn a wider range of coals than a pulverized-coal-fired (PCF) boiler and is simpler to operate and maintain than an IGCC power plant.

By combining the salient features of PFBC and IGCC, a new generation of PFBC plants promises increased efficiency and lower cost, while avoiding the increased complexity and higher cost of the IGCC systems. Foster Wheeler's (Second-Generation) "Advanced" Pressurized Fluidized Bed Combustion concept achieves this goal. The partial conversion of coal to syngas and subsequent firing in a gas turbine at 1288°C (2350°F) increases the thermal efficiency of a PFBC plant to about 45 percent (HHV basis). Studies have further shown that 49 percent (HHV) efficiency can be achieved with high-pressure steam systems and advanced gas turbine technology under development.

The path to successful commercialization of APFBC technology involves conceptual design, pilot-scale component testing, integrated system testing, and demonstration. The developmental programs designed to achieve commercial status of the technology are described in the following sections.

ADVANCED PFBC CONCEPT

In Foster Wheeler's Second-Generation PFBC concept (Figure 1), coal is fed to a pressurized pyrolyzer (carbonizer), where it is converted to a low-Btu fuel gas and char. The relatively low carbon conversion that takes place in the carbonizer results in a simpler sulfur-removal process than is typically required in coal gasification processes. The char (unreacted coal, coal ash, and unreacted/reacted sorbent) that is produced in the carbonizer is transferred to a circulating pressurized fluidized bed combustor (CPFBC), where it is subsequently burned. The fuel gas produced in the carbonizer is cleaned of particulates and alkali and is fired in a specially designed combustor outside a high-temperature gas turbine using the CPFBC flue gas (vitiated air) as the oxidant. Steam is raised and superheated in the CPFBC.

The shaded components in Figure 1 represent the additional elements required to increase the efficiency of first-generation PFBC plants. The redistribution of electric power produced in first-generation PFBC plants (20 percent in the gas turbine/80 percent in the steam turbine) to that produced in second-generation PFBC plants (50 percent in the gas turbine/50 percent in the steam turbine) is shown in the figure.

COMPONENT TESTING—FWDC PILOT PLANT/UTSI

In Phase 1 of a three-phase, U.S. Department of Energy sponsored program, a nominal 500-MW plant was designed, and the costs, operational and environmental performance were compared with a conventional PCF plant with wet scrubbers. The plant is modular, with two parallel power island trains consisting of a carbonizer, CPFBC, and associated hot-gas cleanup systems feeding a gas turbine fired at 1288°C (2350°F) and a heat recovery steam generator

(HRSG). A single reheat steam turbine is powered by the combined steam flows of the two power island trains. About 45 percent of the combined-cycle power is produced by the two gas turbines and 55 percent by the steam turbine. Plant auxiliary power is very low (about 3 percent); the net thermal efficiency is 44.9 percent. The estimated heat rate of the plant is about 18 percent lower than the PCF plant. The results of the conceptual design study confirmed the objectives of the program—to design an APFBC plant with a 45-percent thermal efficiency and a cost-of-electricity (COE) 20 percent lower than a conventional PCF plant with flue gas desulfurization (FGD).

In Phase 2, a 254-mm (10-in.) carbonizer was tested at Foster Wheeler's Research Center in Livingston, New Jersey. Tests were conducted with operating temperatures ranging from 816 to 982°C (1500 to 1800°F) and pressures from 1.01 to 1.42 MPa (10 to 14 atm). Pittsburgh No. 8 coal and Ohio Plum Run dolomite were the predominant feedstocks, although Illinois No. 6 and Eagle Butte (a Wyoming subbituminous) were also tested, along with an Alabama limestone. Carbonizer fuel gas was predominantly carbon monoxide, carbon dioxide, hydrogen, and methane. No hydrocarbon vapors were produced throughout the entire test program—an important finding, since one of the major technology-related issues for this type of plant is the concern that hydrocarbon vapors, if present, could foul the barrier-type filters required to protect the high-temperature gas turbine from particulate erosion and deposition.

The pilot plant carbonizer test results, compared to the carbonizer performance assumptions used in the Phase 1 study, produced a higher fuel gas heating value, a higher sulfur-capture efficiency, and a lower yield of ammonia in the fuel gas. The better sulfur capture and lower ammonia yield (when converted to NO_x) result in lower plant emissions than predicted in the design study. The higher-quality fuel gas translates to a higher topping combustor firing temperature, a further increase in plant efficiency (44.9 to 46.2 percent), and an increase in power production in the gas turbine from 45 to 50 percent.

The carbonizer was subsequently converted to a 203-mm (8-in.) diameter x 11-m (34 ft-6 in.) tall CPFBC, and the CPFBC was tested using petroleum coke, four coals (Pittsburgh No. 8, Illinois No. 6, Kentucky, and Eagle Butte), char (produced in the earlier carbonizer tests), dolomite, and two limestone sorbents. Combustion efficiency was very high (greater than 99.5 percent) for all the fuels tested, including char. Sulfur capture efficiencies were generally high (greater than 96 percent) using Ca/S ratios ranging from 1:1 to 2:1. As a result of the "short" CPFBC height (the carbonizer was converted to the CPFBC), the NO_x and calcium sulfide conversions were not optimized.

Parallel to the pilot plant testing, Westinghouse has conducted topping combustor tests at the University of Tennessee Space Institute (UTSI). The topping combustor must burn low heating value fuel gas delivered from the carbonizer at approximately 870°C (1600°F) and 1.17 MPa (170 psi). The fuel gas entering the topping combustor has been previously cleaned of particulate and alkali, but contains fuel-bound nitrogen present as ammonia. The ammonia is significant because it will selectively oxidize to NO_x if the fuel is burned under the highly oxidizing conditions of standard turbine combustors. The fuel gas must be burned with the hot vitiated air from the CPFBC. The vitiated air has also been cleaned of particulates and alkali, but is partially depleted in oxygen. The 870°C (1600°F) vitiated air must be utilized to cool the topping combustor.

Tests completed with 305-, 356-, and 457-mm (12-, 14-, and 18-in.) diameter multiannular swirl burners (MASBs) using synthetically produced carbonizer fuel gas doped with ammonia confirmed that the MASB can be successfully cooled with 870°C (1600°F) vitiated air (supplemented with additional cooling air at the hottest locations). Good temperature distribution patterns were obtained and stable, complete combustion was achieved. To reduce ammonia conversion, the MASB was redesigned to improve backmixing and increase residence time in the rich zone.

In Phase 3, scheduled to begin in late 1994, a 254-mm (10-in.) I.D. carbonizer and 356-mm (14-in.) I.D. CPFBC—each with gas cleanup and solids feeding systems—will be tested in an integrated mode at the Foster Wheeler Research Center.

INTEGRATED TESTING—WILSONVILLE POWER SYSTEMS DEVELOPMENT FACILITY

In parallel with the pilot plant testing, work is under way to design and build a larger, integrated test facility. The test facility is part of the Power Systems Development Facility (PSDF) to be operated by Southern Company Services at Wilsonville, Alabama. The $145 million PSDF consists of several "modules" for long-term testing of APFBC, advanced gasification, hot-gas cleanup systems, and fuel cells. The PSDF is a joint, cost-shared effort between the DOE, the EPRI, and industry.

Most of the second-generation PFBC components will be tested in the Wilsonville configuration. The exception is a steam turbine is not incorporated in the design. The APFBC plant will provide the first full integration of the gas side of the power island—that is, operation of a gas turbine topping combustor with hot pressurized fuel gas from the carbonizer and hot pressurized flue gas from the CPFBC. A key element of the program is long-term testing and assessment of particulate control devices (PCDs) that directly supports DOE's Clean Coal program. The nominal 7-MW APFBC plant is scheduled to begin operation in late 1995.

The design coal and sorbent are Illinois No. 6 and Longview limestone. Eagle Butte subbituminous coal is an alternative fuel. The plant is designed for a coal feed rate of 0.69 kg/s (5500 lb/h) and a sorbent feed rate of 0.13 kg/s (1050 lb/h). Provision has been made in the design to test the CPFBC under low excess-air conditions, feeding coal and sorbent directly to the CPFBC.

The carbonizer, like the Livingston pilot plant unit, is a "jetting" fluidized bed pyrolyzer without heat-transfer surface. The refractory-lined vessel has a bed section (lower part) [approximately 914 mm (3 ft) diameter], 14.6 m (48 ft) high and a disengagement section (upper part) [approximately 1.22 m (4 ft) diameter]. The carbonizer is designed to feed coal pneumatically in the bottom of the vessel; alternate feed points are located radially at two different elevations. The feed system has been designed to accommodate both dry and paste feed.

The CPFBC, shown in Figure 2, is a refractory-lined vessel with an 838-mm (33-in.) diameter upper section. The integrated heat exchanger is a refractory-lined vessel that contains four cells—an inlet, an outlet, and two heat transfer cells. Heat is removed in the integrated heat exchanger by a once-through condensate system. The unit has been designed so that it can operate between 20- and 300-percent excess air to test both first-generation and advanced PFBC concepts. An oxidizer/cooler cools the CPFBC bed material from 871 to about 260°C (1600 to about 500°F) and transports the bed (ash) to a lockhopper for discharge from the unit.

High-temperature gas cleaning (HTGC) systems control particulates and alkalies. Two independent HTGC systems handle the carbonizer fuel gas stream and the CPFBC flue gas stream. Each HTGC system consists of a cyclone, PCD, and alkali getter.

An Industrial Filter & Pump Mfg. Co. low-density fiber ceramic candle filter design is being used as the carbonizer PCD. The refractory-lined filter vessel (Figure 3) has a 1.5-m (60-in.) diameter and contains candles arranged in six groups for back-pulse cleaning. The candles are of aluminosilicate fiber construction, with binders of silica and alumina. The monolithic flared flange and end cap of the candle are of densified ceramic fiber construction, as are the tubesheet and the candle retainer.

PCD service for the CPFBC will be provided by a Westinghouse ceramic candle filter consisting of a refractory-lined pressure vessel containing six arrays, or "clusters," of 60-mm (2.36-in.) diameter x 1.5-m long (59-in.) diameter candle elements. The individual clusters are supported from a high-alloy tubesheet and expansion assembly that spans the 3.1-m (10.2-ft) pressure vessel and separates the "clean" and "dirty" gas. The Westinghouse cluster concept is illustrated in Figure 4.

The alkali getters are sorbent packed beds contained in vertical, refractory-lined pressure vessels. The sorbent material reacts irreversibly with sodium and potassium vapor-phase compounds at high temperature.

The topping combustor is designed to operate with a vitiated air temperature of 1600°F, however, there is provision to introduce compressor air upstream of the topping combustor to cool the vitiated air to about 1400°F before it enters the topping combustor. The topping combustor is fired at an exhaust gas temperature of 1288°C (2350°F), the firing temperature for a commercial plant, using 899°C (1650°F) carbonizer fuel gas. While the advanced PFBC commercial plant uses an advanced industrial turbine with a turbine inlet temperature of 1288°C (2350°F), Wilsonville uses a turbine which operates at a maximum temperature of 1080°C (1975°F). Wilsonville will demonstrate that a firing temperature of 1288°C (2350°F) is viable with respect to emissions and burner design. However, because of the lower turbine operating temperature required, part of the compressor air will be used to cool the exhaust gas downstream of the topping combustor.

The gas turbine generator set is a modified Allison Model 501-KB5 gas turbine, which drives a synchronous generator through a speed-reducing gearbox. The hot exhaust gas from the topping combustor is expanded through the gas turbine, powering both the electric generator and the air compressor. Air from the compressor supplies all APFBC plant process air requirements.

DEMONSTRATION

A 95-MW plant utilizing Foster Wheeler's Advanced PFBC technology will be demonstrated under the U.S. Department of Energy's Clean Coal Technology V (CCT V) program. The proposed plant will operate in a cogeneration mode, providing electric power and extraction steam for manufacturing. Following a 30-month demonstration period, the plant will continue to operate on a commercial basis. The plant is scheduled to start up in 1998.

Coal paste and limestone are fed to the carbonizer, and the char from the carbonizer, additional coal paste, and limestone are burned in the CPFBC. The carbonizer is a refractory-lined vessel approximately 14 m (46 ft) high. The lower (bed) section of the carbonizer is 2.6-m (8-ft) diameter while the upper section of the vessel expands to 3.3-m (10-ft) diameter. The gas in-bed residence time is about 5 seconds, equivalent to the pilot plant and Wilsonville designs. The CPFBC is a Foster Wheeler single-vessel design incorporating membrane wall construction, cyclone, "J" valve, integrated heat exchanger (INTREX™), and ash stripper/cooler—all housed in a pressure vessel.

The CPFBC generates steam from the waterwalls and INTREX™, and additional steam is generated in the HRSG to drive the steam turbine generator. At full load, Four Rivers will generate about 70 MW of electricity and provide 39.1 kg/s (310,000 lb/h) steam at 1.31 MPa absolute (190 psia) and 215°C (420°F). The gas turbine generates 38 MW, and the extraction/condensing steam turbine generates 32 MW.

The particulate matter in the carbonizer fuel gas is removed using multiple ceramic candle filter systems supplied by Westinghouse. The CPFBC flue gas particulate matter is removed using a proprietary ceramic candle filter design supplied by Lurgi-Lentjes-Babcock (LLB), formerly Deutsche Babcock Energie. Seven 457-mm (18-in.) MASBs fire the carbonizer fuel gas in the topping combustor. The hot exhaust gas from the topping combustor drives a Westinghouse Model 251 gas turbine.

BEYOND DEMONSTRATION

Following demonstration, the APFBC technology will be ready for rapid world-wide commercialization. When proved successful, the technology will allow the effective use of high-sulfur coal, lower power generation costs, reduce emissions, extend fuel supplies, and provide utilities and industry with a reliable option for repowering and new generation capacity. As coal continues to play an important role in power generation, Advanced Pressurized Fluidized Bed Combustion will provide one of the most cost-effective and environmentally friendly technologies in the next century. Foster Wheeler is committed to the successful commercialization of this technology.

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ADVANCES IN THE SHELL COAL GASIFICATION PROCESS

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Process Summary

The Shell Coal Gasification Process (SCGP) is a dry-feed, oxygen-blown, entrained flow coal gasification process which has the capability to convert virtually any coal or petroleum coke into a clean medium Btu synthesis gas, or syngas, consisting predominantly of carbon monoxide and hydrogen.

In SCGP, high pressure nitrogen or recycled syngas is used to pneumatically convey dried, pulverized coal to the gasifier. The coal enters the gasifier through diametrically opposed burners where it reacts with oxygen at temperatures in excess of 2500°F. The gasification temperature is maintained to ensure that the mineral matter in the coal is molten and will flow smoothly down the gasifier wall and out the slag tap. Gasification conditions are optimized, depending on coal properties, to achieve the highest coal to gas conversion efficiency, with minimum formation of undesirable byproducts.

The hot syngas exiting the gasifier is quenched to below the softening point of the slag and then cooled further in the syngas cooler. Entrained flyash is removed to less than 1 ppm using ceramic candle filters. Downstream syngas treating includes low level heat recovery and conventional cold gas cleanup to minimize trace metal emissions and to remove chlorides, and sulfur and nitrogen compounds. Essentially all of the nitrogen is ultimately converted to molecular nitrogen, and essentially all of the sulfur is recovered as salable, elemental sulfur. Slag and flyash are also recovered as marketable by-products. A simplified SCGP flow scheme is shown in Figure 1.

Technology Development

Research on the Shell Coal Gasification Process began in 1972, based on Shell's extensive experience with oil gasification. In 1976, a 6 TPD process development unit was placed in operation at Shell International's Amsterdam laboratory, and in 1978, a 150 TPD pilot plant was started up near Harburg, Germany. The Harburg unit, which operated until 1983, demonstrated the key technical features of the SCGP technology.

A very important element in the SCGP development program was the construction and operation of SCGP-1, the 250 TPD demonstration unit which operated between 1987 and 1991 at Shell Oil's Deer Park Manufacturing Complex near Houston, Texas. SCGP-1 was based on a scaled down version of commercial unit. During its 15,000 hours of operation, SCGP-1 clearly demonstrated the reliability, flexibility, efficiency, and environmental superiority of SCGP. Coal to clean gas efficiencies were typically above 80% and sulfur removal efficiencies were consistently above 99% for the 18 diverse feedstocks gasified at SCGP-1. The SCGP-1 feedstocks included domestic coals ranging from lignite to high sulfur bituminous coals, three widely traded foreign coals, and petroleum coke.

The extensive environmental, engineering and operating data collected during the SCGP-1 operating program provide the basic information necessary to permit, design, construct, and operate future SCGP plants. Moreover, the SCGP-1 program yielded a number of process improvements and innovations which have since been incorporated into commercial designs.

The Demkolec Project

The first commercial application of SCGP is the Demkolec Project, a 253 MW integrated gasification combined cycle (IGCC) power plant located in the Netherlands. Demkolec B.V., a wholly owned subsidiary of the Dutch Electricity Generating Board, selected SCGP as the coal gasification technology for their project in 1989 and executed an SCGP license agreement with Shell International later that year. Environmental permits based on NO_x emissions of 0.17 lb/MM Btu and SO_2 emissions based on 0.06 lb/MM Btu of design coal were obtained in April 1990. Construction began in July 1990, commissioning was completed in 1993 and startup was initiated in late 1993. An extensive, three-year demonstration program has been identified and is underway.

The Demkolec Project employs a single SCGP gasifier to fuel a Siemens V94.2 combustion turbine coupled with steam turbine and generator. The SCGP plant is fully integrated with the combined cycle plant, including the boiler feed water and steam systems; additionally, the compressed air for the high pressure air separation unit is supplied by extraction air from the combustion turbine air compressor.

The Demkolec Project features a multiple burner gasifier scaled up from the SCGP-1 gasifier to 2000 TPD coal. Also, the Demkolec Project includes a number of process improvements which were successfully demonstrated during SCGP-1 operation. Among these are:

- increased slagging efficiency and a reduction in slag entrainment;
- dry solids removal which offers higher flyash removal efficiency and lower cost;
- dry flyash recycle to improve carbon conversion and slagging efficiency;
- flux addition to promote slag flow and optimize gasification conditions, depending on coal properties;
- catalytic hydrolysis of hydrogen cyanide (HCN) and carbonyl sulfide (COS) to reduce corrosion, reduce emissions and simplify gas treating;
- zero aqueous process discharge for environmental considerations; and
- a turbine lead/gasifier follow control system for load following.

Additional SCGP improvements and innovations have been developed since the Demkolec design was completed with the aim of further reducing costs and improving performance. In the last several years, a number of design and optimization studies and capital cost estimates have been carried out for Shell-based IGCC systems with different engineering firms and equipment suppliers, including General Electric, Westinghouse, Air Products, Fluor/Daniel, Black & Veatch, and Bechtel, and with support from the Electric Power Research Institute. Developments in SCGP, improvements in gas turbine performance, and the ongoing experience of equipment manufacturers have all contributed to the Shell Synthetic Fuels' commercial design for SCGP.

Shell Synthetic Fuels' SCGP Commercial Design

The SCGP commercial design is the latest effort by Shell Synthetic Fuels Inc. to combine SCGP technology developments subsequent to the SCGP-1 program and the Demkolec Project design with other related IGCC improvements. The SCGP commercial design is based on a single train SCGP plant coupled with a high pressure air separation unit (ASU) to fuel a single combustion turbine operating in combined cycle service. If the GE frame 7FA combustion turbine is used, IGCC net power output is estimated to be approximately 265 MW. With a high sulfur Illinois coal, heat rate is estimated at slightly less than 8150 Btu/kWh. Even lower heat rates can be expected with most other bituminous coals.

The principal objective of the SCGP commercial design is to deliver competitive capital and maintenance costs with superior efficiency and environmental performance. Each of the main systems associated with a Shell-based IGCC plant is reviewed below.

Coal Pulverizing and Drying

Roller or bowl mill pulverizers have been demonstrated in higher capacity service in the last several years. The SCGP commercial design includes two large commercial scale pulverizers for a single gasifier/gas turbine train. (Three pulverizers would be premised for a two gasifier/gas turbine system.) Each pulverizer has excess capacity so that sufficient availability is provided without the need for an additional pulverizer. Heat and nitrogen savings have also been designed into the drying system for higher moisture content coals.

SCGP Gasifier

The SCGP-1 unit was shutdown in March 1991. Considerable analyses of the later stages of the SCGP-1 operation showed that the cold gas efficiency could be further increased and that the scaleup/severity parameters were less restrictive than anticipated. These less conservative scaleup rules allow reduced gasifier physical dimensions for a design coal/syngas rate. Further engineering studies into the results of the gasifier scaleup tests at SCGP-1 have led to a more compact gasifier design, while at the same time leading to increased syngas production. Gasifier materials' life is extended by operating the gasifier cooling medium at lower pressure.

Syngas Cooling and Dry Solids Removal

The SCGP dry coal feed system leads to very high coal to gas conversion efficiencies as well as gasifier exit temperatures which are higher than those from coal slurry feed systems. The high gasifier exit temperature and low moisture content of the raw syngas allow most of the waste heat to be recovered at high levels through syngas cooling, at a relatively modest cost. Extensive low level heat utilization is not required to achieve high thermal efficiencies, Consequently, for SCGP, the cost of syngas cooling will almost always be justified by the value of the high level steam produced. Clearly, however, the benefits of syngas cooling can be enhanced by reducing equipment capital and maintenance costs.

The syngas cooling equipment demonstrated at SCGP-1 and employed in the Demkolec Project is a series of water wall exchangers including superheat, evaporation and boiler feed water economizers. Cost/benefit studies led to the conclusion that, where SCGP can be closely heat integrated with the combined cycle plant, the SCGP steam should be superheated in the combined cycle heat recovery steam generator (HRSG) rather than in the syngas cooler. In the Demkolec IGCC Project, the SCGP syngas cooler steam will be mildly superheated, then sent to the HRSG for further superheating.

Second, early plant performance at SCGP-1 and subsequent engineering studies identified that dry solids removal with ceramic candle filters at an intermediate temperature offered SCGP the opportunity to change the economizers from water wall to shell and tube exchangers. Further equipment developments in hot gas particulate removal identified that the evaporator of the syngas cooler could be located downstream of the filter and utilize relatively dust free firetube exchange. Each study led progressively to a better understanding of the tradeoffs between the costs of the filter system and the high temperature exchange surfaces.

The SCGP commercial design uses a dust laden, raw gas firetube exchanger downstream of the conventional recycle gas quench section, followed by dry flyash removal. Further cost reductions were achieved in the lockhopper system used for flyash recycle through scaleup studies on the continuous ash pressure letdown system demonstrated at SCGP-1. Additional low level heat recovery sources have been identified downstream of dry solids removal and may be included in the integrated boiler feed water/steam cycle if the capital costs are justified by the efficiency gains.

Dry Chloride Removal

Chloride in the coal vaporizes in the reducing atmosphere of the gasifier and most of it appears in the form of hydrogen chloride. Past practice has been to wash out the chloride and neutralize the acid in a wet gas cleanup section downstream of the syngas cooler/dry solid removal sections. Depending on the level of chloride in the coal, it can be more cost effective to utilize a dry chloride removal technique with a sorbent. Dry chloride removal offers the additional advantages of reducing catalyst poisons for downstream catalyst beds and of allowing more low level heat recovery from the raw gas.

Cold Gas Cleanup

Very high sulfur removal efficiencies are achievable with the SCGP cold gas cleanup system. Either of two Shell solvents can be used to hydrolyze trace amounts of carbonyl sulfide in the syngas to hydrogen sulfide and then remove the hydrogen sulfide through absorption. Recent studies have premised a total sulfur level of 20 ppm or less in the clean syngas, which allows additional low level heat recovery in the HRSG. In the SCGP commercial design a proprietary system for removing volatile metals such as mercury and arsenic has been combined with the SCGP cold gas cleanup system to further reduce emissions of hazardous air pollutants (HAPs).

Integration of SCGP with Combined Cycle and Air Separation Units

The General Electric 7F and the Westinghouse 501F gas turbines provide high fuel gas to electricity generating efficiency and improved combined cycle performance. The increased gas turbine performance has served to increase net IGCC power output which has in turn helped to reduce the IGCC $/kW cost. Additional IGCC cost and performance benefits can be realized through careful integration of the three basic technologies: SCGP, air separation, and combined cycle power generation. Figure 2 illustrates a highly integrated Shell-based IGCC power plant.

Turbine simulation studies have shown that the clean SCGP coal gas can be diluted with either nitrogen or water to reduce NOx formation and at the same time provide low CO emissions over a wide range of performance conditions. Recent studies have concluded that return of the excess nitrogen from the air separation unit to the combustion turbine is most advantageous for a Shell-based IGCC plant and that saturation of the return nitrogen to the degree desired for gas turbine operation is more attractive than fuel gas saturation and can assure a more reliable fuel gas composition for combustor design and control. Since there is little low level heat for fuel gas saturation in SCGP, the lowest overall IGCC heat rate is obtained with 100% air extraction from the gas turbine for a pressurized air separation unit (ASU), as will be practiced in the Demkolec Project. However, higher net IGCC power output can be achieved by providing the ASU with its own air compressor. The optimum level of air extraction will in fact depend on the specific situation and must be determined as part of an optimized Shell-based IGCC plant design.

Another recent development in Shell-based IGCC plant design derives from the fact that the SCGP syngas composition is very constant over a wide operating range. Combined with new gas turbine control systems, this has led to reductions in turbine fuel gas control valve pressure, which in turn leads to similar reductions in gasifier design pressure and cost.

Environmental Attributes

Environmental emissions of Shell-based IGCC are estimated to be extremely low. Total SO_2 emissions of 0.05 lb/MM Btu or less are achievable, corresponding to greater than 99.5% sulfur removal efficiency. NO_x emissions can be controlled to 0.09 lb/MM Btu (corresponding to 25 ppmv in the HRSG flue gas) or less, and hazardous air pollutant emissions as defined in the 1990 Clean Air Act Amendments are expected to be less than 0.5 tons/year for a nominal 265 MW Shell-based IGCC plant.

As shown in Figure 3, the estimated air emissions from a Shell-based IGCC power plant are well below the regulatory limits and in fact are much closer to those from a natural gas-fired power plant than from a typical coal-based facility. Moreover, long term, on-site storage of solid byproducts is not required since slag, flyash and elemental sulfur are all marketable products.

Conclusions

The first commercial application of the Shell Coal Gasification Process and the world's first fully commercial IGCC facility is Demkolec's 253 MW IGCC power plant in the Netherlands. Experience from the Demkolec Project has provided the foundation for other Shell-based IGCC commercial projects.

The Shell Synthetic Fuels' SCGP commercial design, which includes a number of technology improvements contributing to lower costs, higher efficiency and reduced emissions compared to earlier designs, is now available. Improvements include:

- a more compact gasifier design, aimed at reducing capital cost and increasing coal to gas conversion efficiency;
- revised syngas cooler design to reduce capital costs and maintenance requirements;
- continuous flyash letdown to improve reliability and reduce maintenance requirements;
- dry chloride removal to further simplify downstream gas treating;
- techniques to increase efficiency and reduce formation of undesirable byproducts in the gasifier;
- methods for improved removal and recovery of volatile metals such as mercury and arsenic to reduce HAP emissions; and
- integration of SCGP with the combined cycle and air separation units to minimize \$/kW cost, while maintaining performance and operability requirements.

FIGURE 1
SHELL COAL GASIFICATION PROCESS
PROCESS FLOW SCHEME

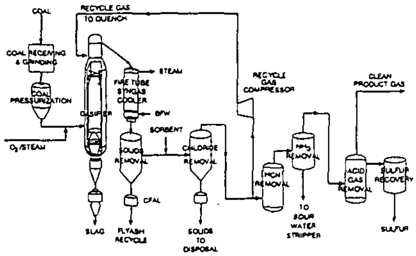


FIGURE 2
HIGHLY INTEGRATED SHELL COAL GASIFICATION
COMBINED CYCLE POWER PLANT CONFIGURATION

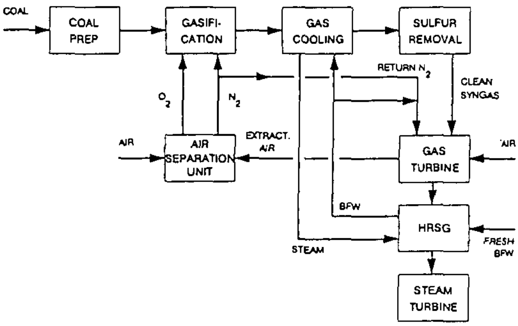
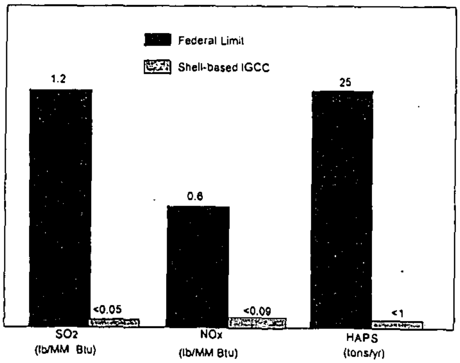


FIGURE 3
SHELL-BASED IGCC AIR EMISSIONS



AMERICAN ELECTRIC POWER
PRESSURIZED FLUIDIZED BED COMBINED CYCLE
TECHNOLOGY STATUS

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Keywords: Clean Coal Technology, Pressurized Bubbling Bed, Combined Cycle

INTRODUCTION

The Ohio Power Company's Tidd Pressurized Fluidized Bed Combined Cycle (PFBC) program continues to be the only operating PFBC demonstration program in the nation. The 70 MWe Tidd Demonstration Plant is a Round 1 Clean Coal Technology Project constructed to demonstrate the viability of PFBC combined cycle technology. The plant is now in its fourth year of operation. The technology has clearly demonstrated its ability to achieve sulfur capture of greater than 95%. The calcium to sulfur molar ratios have been demonstrated to exceed original projections. Unit availability has steadily increased and has been demonstrated to be competitive with other technologies. The operating experience of the first forty-four months of testing has moved the PFBC process from a "promising technology" to a viable, proven option for efficient, environmentally acceptable base load generation.

Funding for the $210 million program is provided by Ohio Power Company, The U.S. Department of Energy, The Ohio Coal Development Office, and the PFBC process vendors - Asea Brown Boveri Carbon (ABBC) and Babcock and Wilcox (B&W).

PLANT DESCRIPTION

The project involves the repowering of a 1940's vintage pulverized coal plant with PFBC components. The original Tidd plant consisted of two 110 MWe steam turbine generators supplied with steam by conventional coal fired boilers. The unit 1 steam turbine was repowered at approximately 50% capacity by the addition of a PFBC combustor steam generator and a gas turbine exhaust economizer. Other additions included in the AB scope of supply were the gas turbine and generator, the coal preparation system, the coal and sorbent feed systems, the gas cleaning system, and the cyclone and bed ash removal systems. The major balance of plant improvements included the addition of an electrostatic precipitator, combustor building, bed ash and cyclone ash silos, and sorbent preparation facilities. Modification of the coal and sorbent storage areas and a revamped control room completed the needed improvements for the conversion. The remainder of the balance of plant utilized the original Tidd balance of plant components and systems.

The PFBC Power Island (Figure 1), which was incorporated into the existing plant, was designed to provide 440,000 pounds per hour of steam flow at 1300 psia and 925°F. Plant generation output was expected to be 72.5 MWe gross (57.1 MWe from the steam turbine generator and 15.4 MWe from the gas turbine generator).

Air, at approximately 175 psia, is provided to the combustor by the gas turbine compressor through the outer annulus of a coaxial air/ gas pipe. Inside the combustor vessel, the air is ducted into the boiler where it fluidizes the bed materials and provides oxygen for combustion. The bed design temperature is 1580°F, which was established by the maximum acceptable gas turbine inlet temperature. This temperature is well above the minimum coal combustion temperature and provides sufficient margin to preclude melting of the coal ash constituents. In addition, this temperature is conducive to a relatively high reaction rate for SO_2 capture by direct sulfation of the calcium carbonate in the sorbent, while being well below the temperature at which alkalies vaporize and present a corrosion problem for the gas turbine. Formation of thermal NOx is essentially nil due to the low combustion temperature and the reduction of much of the NOx formed from nitrogen in the coal to N_2 and O_2 at char sites in the bed. Seven parallel strings of gas cleaning cyclones remove 99% of the ash elutriated by the gas leaving the bed. Six of the strings consist of a primary and a secondary cyclone, the seventh is comprised of a primary cyclone in series with an experimental ceramic Advanced Particle Filter (APF).

All of the cyclones are located in the combustor vessel. The APF is located outside the combustor in a separate pressure vessel. The gas from all seven strings is combined inside the pressure vessel and routed to the gas turbine via the coaxial air/gas pipe. The gases are expanded through an ABB Stal GT-35P gas turbine, which produces shaft power to run the gas turbine compressor (approximately 2/3 of the power at full load) and to drive the gas turbine generator (remaining 1/3 of the power). The turbine exhaust gases then pass through the economizer where excess heat is transferred to the feedwater and then through the electrostatic precipitator for further particulate collection. The gases then are ducted to Cardinal Unit No. 1 where they are combined with that unit's exhaust stream and exit to atmosphere via the Cardinal stack.

The steam cycle is a Rankine cycle with a subcritical once-through boiler. Condensate is heated by two stages of low pressure heaters and a gas turbine intercooler as it is pumped to the deaereator. A single high pressure heater and the turbine exhaust gas economizer raised the final feedwater temperature to approximately 480°F. The feedwater then passes through the boiler bottom hopper and furnace wall enclosures where additional subcooled preheating occurs. The feedwater then enters the in-bed evaporator tubes where the steam is generated and attains a slight degree of superheat. The steam then passes through the in-bed primary superheater, is attemperated and attains final steam temperature in the in-bed secondary superheater. At steam flows below 40% capacity, a circulation pump maintains sufficient flow rate through the evaporator circuits for cooling protection. The resultant moisture in the evaporator outlet steam is separated by centrifugal action in a vertical separator.

Coal is injected into the fluidized bed as a paste nominally containing 25 percent water by weight. Raw coal of 3/4 inch top size is fed to a double roll crusher which reduces the material to minus 1/4 inch. The crushed coal is conveyed to a screen to collect oversized material then to a mixer where water is added to make the paste. A recycle line, which is located upstream of the screen, returns a portion of the material to the crusher. Recycle is regulated to attain a sufficient quantity of coal fines, which are necessary to make a cohesive and pumpable coal paste. The paste is fed from the mixer into two interconnected surge tanks which supply six hydraulically driven piston pumps. These pumps feed the paste to individual fuel nozzles which deliver the paste into the fluidized bed just below the tube bundle.

The sorbent, which is generally dolomite, is crushed to minus 1/8 inch size and dried in a hot air swept hammermill crusher. This material is then injected into the fluidized bed via alternating dual lockhoppers that feed a dilute phase pneumatic transport system. The original transport system design splits the flow into two feed nozzles, however, the system has recently been modified to provide a total of four feed nozzles.

Material is drained from the bed to maintain the bed level. This "bed ash" accounts for approximately 40% of the total ash and is generally 99% larger than 60 mesh (250 microns). The ash is drained in a controlled manner by gravity via two parallel lockhoppers. Material elutriated from the bed and collected in the cyclones, approximately 60% of the ash, is generally 99% smaller than 60 mesh. This "cyclone ash" is removed by means of a pneumatic transport system which depressurizes and cools it.

BED PROCESS FINDINGS

Post-Bed Combustion

Initial operation of the unit revealed that combustion was occurring beyond the bed resulting in excessively high temperatures of the gas in selective cyclone strings and in the primary cyclone dip legs. The dip leg combustion was attributed to excessive unburned carbon carryover; whereas, the gas stream combustion was attributed to carryover of unburned volatiles. Both of these phenomenons were attributed to high localized fuel release combined with rapid fuel breakup and devolitization. Insufficient oxygen in these localized regions resulted in plumes of low O_2 gas with unburned volatiles and fine char. This was documented through oxygen measurements taken in the freeboard above the fuel nozzle discharge points. This problem was minimized through improved fuel splitting, installation of a steam induced freeboard gas mixing system, and improvements in the coal paste quality. The latter factor proved to have the greatest impact on reducing the degree of post bed combustion.

Recently, the unit has operated for extended periods with no signs of post bed combustion. However, upsets in coal paste preparation still result in upward swings in freeboard gas temperature. Such swings pose a potential trip risk at full bed height due to excessive gas turbine temperatures. At lower bed heights, these swings are not a problem, since the freeboard temperature runs well below the bed temperature due to the convective cooling action of the tubes above the top of the bed. The post bed combustion phenomenon is understood to the extent that operations personnel are able to monitor plant conditions and take early action to prevent or mitigate such occurrences.

Sinter Formation
The formation of small quantities of hollow egg shaped agglomerates, in the range of 1 - 2 inches in size (Sintering), has been observed throughout the operation of the unit. However, these did not pose a major operating problem at low bed levels, since the formation rate was slow and sinters drained from the bed at a rate which prevented any significant buildup. In late 1993 and early 1994, sintering became a significant operating problem. The rate of sinter formation increased greatly when the unit was operated at higher bed levels. At these higher formation rates, sinters accumulated in the bed causing bed conditions to deteriorate. Uneven bed temperatures, decaying bed density, and a reduction in heat absorption are common symptoms of bed sintering.

Initial speculation as to the cause of high load sintering focused on the higher local heat release associated with higher loads and insufficient fuel splitting. Modifications were made to both the fuel nozzles and the fuel distribution baffles to improve mixing. However, no significant improvements were observed. The hypothesis that poor bed mixing and less than ideal fluidization were key contributors was subsequently developed. A series of performance tests were proposed to demonstrate that better mixing would significantly reduce sintering. Improvements in fluidization were achieved by reducing the size consist of the dolomite feed, thereby reducing bed size consist, while maintaining fluidizing velocity constant. The introduction of finely crushed dolomite (-12 mesh) versus the normal coarse crush (-6 mesh) significantly reduced sintering to the extent that full bed temperature of $1580^{0}F$ could be maintained with no evidence of sintering.

The most severe incidents of sintering all occurred when feeding limestone. It is postulated that the reduced amount of MgO in the limestone may contribute to the uncontrolled sintering. The mechanism for this sintering is likely fluxing of the potassium-alumina-silicate clays in the coal ash by calcium from the sorbent. The nuclei of the sinters appear to be coal paste lumps which become sticky and collect bed ash on their surface. The coal then burns away, leaving the coal ash to react with the bed material. The less aggressive sintering with dolomite is explained by the fact that increased quantities of MgO tend to raise the melting temperatures of $CaO\text{-}MgO\text{-}Al_2O_3$ mixtures. In evaluating the sintering problem, it must be recognized that the extremely low ash fusion temperature of the Pittsburgh No. 8 coal burned at Tidd is likely a major contributing factor to sintering.

UNIT PERFORMANCE
Testing has progressed significantly since completion of the first three years of operation. The improved unit availability has provided the opportunity to conduct a greater number of varied performance tests than was previously possible. The most recent series of tests, were devised to address sintering issues by reducing the size consist of the bed. The finer sorbents, which were specified and purchased with a narrow size consist range, proved to be successful in addressing sintering while at the same time demonstrating exceptional improvement in the Ca/ S molar ratios.

The data clearly shows a significant improvement in sulfur capture resulting from the injection of finer dolomitic material as a the sorbent. The improvement in performance is significantly greater than can be explained solely by the larger sorbent exposed area due to the finer material. The noted improvement in performance must also be the result of significant improvements in bed fluidization and mixing. Especially when a number of other recorded system parameters such as steam generation and bed/evaporator temperature profiles also point to enhanced bed dynamics.

Performance testing has been limited to approximately 115 inches due to summer limitations on the gas turbine. However, overall testing has provided a sufficient basis to confirm the correlations, previously developed at Grimethorpe, thereby permitting extrapolation of the data to varied temperatures, bed heights, and sulfur captures. Figures 2 and 3 show sorbent utilization (Ca/S) versus bed height for 90 and 95 percent sulfur capture.

The affect of sorbent feed size consist on sorbent utilization is clearly seen. Reducing sorbent size consist from coarse sorbent (-6 mesh) to finer sorbent (-12 to -20 mesh) results in significant increases in sorbent sulfation and therefore reduced sorbent feeds to achieve a predetermined level of sulfur capture. In addition to sorbent size consist effect on sorbent utilization, Figures 3 and 4 show the impact of sorbent reactivity. National Lime Carey dolomite (NL) has generally been demonstrated to be less reactive than the Plum Run Greenfield dolomite (PRG).

CONCLUSION

The Tidd PFBC Demonstration Plant has now achieved over 9921 hours of coal fired operation. Approximately 3865 hours, including the longest continuous run of 1070 hours, were achieved during the last ten months of operation. Unit availability during this period was approximately 52%.

A total of 62 performance tests have been conducted to date. Eleven tests were completed during the latest run. Test objectives during the run were aimed at reducing bed sintering and improving sorbent utilization. The tests were conducted using -12 to -20 mesh sorbent. The finer sorbent was expected to improve bed mixing and fluidization, thereby mitigating sintering and improving sorbent utilization. Bed conditions improved significantly and operation at 1580^{0}F bed temperature was achieved with little, if any, bed sintering. Performance testing was completed at 1580^{0}F, 115 inch bed level and 90% sulfur capture. The results showed a marked improvement in sorbent utilization, Ca/S molar ratios around 1.3 were indicated. This data extrapolates to Ca/S molar ratios, at full bed heights, of 1.2 and 1.5 for 90% and 95% sulfur capture respectively.

In addition to improved sorbent utilization, the unit demonstrated better heat transfer than had previously been achieved as well as a more homogeneous bed temperature distribution.

The reliability of PFBC has and continues to be demonstrated. The process, which was initially demonstrated in early operation, has been refined and optimized to the point were PFBC is competitive with all other technologies for both low and high sulfur coals. Expected enhancements of both systems and process are expected to further improve sorbent utilization and system performance beyond the levels already achieved while continuing to demonstrate the service life of both the gas turbine and the boiler tube bundle. The process has been demonstrated to be environmentally sound, cost effective, and capable of achieving the reliability and availability required in a power generating unit. Commercial deployment remains the only hurdle left to PFBC technology.

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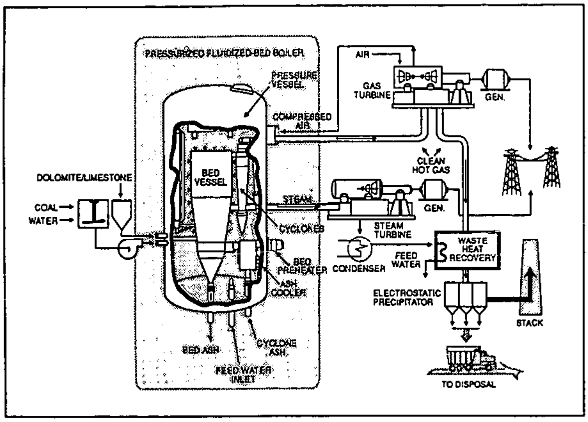

FIGURE 1 - TIDD PFBC COMBINED CYCLE

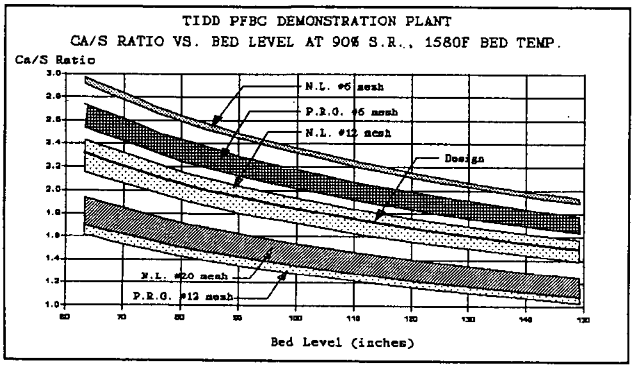

FIGURE 2

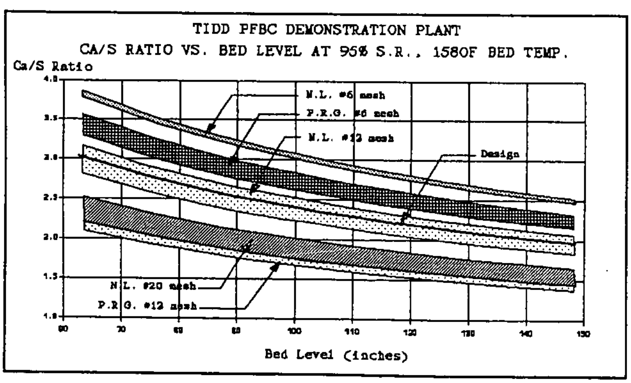

FIGURE 3

THE POWER SYSTEMS DEVELOPMENT FACILITY AT WILSONVILLE, ALABAMA

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INTRODUCTION

One of the Morgantown Energy Technology Center's (METC's) goals is to: "Commercialize Advanced Power Systems with improved environmental performance, higher efficiency, and lower cost." Advanced coal-based power generation systems include Integrated Gasification Combined Cycle (IGCC), Pressurized Fluidized-Bed Combustion (PFBC), and Integrated Gasification/Fuel Cell systems. The strategy for achieving this goal includes: (1) Show the improved performance and lower cost of Advanced Power Systems through successful Clean Coal Technology demonstration projects, (2) Build and operate Technology Integration Sites in partnership with U.S. Industry (these sites will resolve key technology issues and effect continuous product improvement, and these partnerships result in leveraging of research and development (R&D) funds), and (3) Set up partnerships with other agencies and organizations such as Electric Power Research Institute (EPRI) to leverage R&D funds and skills.[1]

Demonstration of practical high-temperature particulate control devices (PCD's) is crucial to the evolution of advanced, high-efficiency coal-based power generation systems. There are stringent particulate requirements for the fuel gas for both turbines and fuel cells. In turbines, the particulates cause erosion and chemical attack of the blade surfaces. In fuel cells, the particulates cause blinding of the electrodes. Filtration of the incoming, hot, pressurized gas is required to protect these units. Although filtration can presently be performed by first cooling the gas, the system efficiency is reduced. Development of high temperature, high pressure, is necessary to achieve high efficiency and extend the lifetime of downstream components to acceptable levels.

THE POWER SYSTEMS DEVELOPMENT FACILITY - A TECHNOLOGY INTEGRATION SITE

The Power Systems Development Facility (PSDF) combines a number of pilot-scale test facilities at a single site to reduce the overall capital and operating cost compared to individual stand-alone facilities. Combining all of these pilot-scale facilities in a new 60x100 foot structure and sharing resources common to different modules, such as coal preparation, are estimated to save nominally $32 million over the cost of separate facilities. The PSDF will be located 40 miles southeast of Birmingham, Alabama, at Southern Company's Clean Coal Research Center in Wilsonville, Alabama.

The objective is to establish a flexible test facility that can be used to develop advanced power system components such as high-temperature, high-pressure particle control devices, evaluate advanced power system configurations, and assess the integration and control issues of these advanced power systems. The facility will also support the Department of Energy (DOE) Clean Coal Program.

The PSDF will consist of five modules. Two of the modules will produce particulate-laden gas, an Advanced Pressurized Fluidized-Bed Combustion (APFBC) module and an Advanced Gasifier module. The PCD's will be in a Hot-Gas Cleanup module, and there will also be a Compressor/Turbine module, and a Fuel Cell module. Four separate PCD technologies will be tested at the facility using the gas from the two gas-producing modules.

The PSDF project team is led by Southern Company Services (SCS) and is comprised of M. W. Kellogg, Foster Wheeler, Westinghouse, Allison, Southern Research Institute (SRI), and several developers of PCD's. The facility design reflects the Power System's R&D needs as identified by DOE and EPRI. The involvement of these diverse private sector organizations will ensure that the duration, scale, and results of the PSDF test program will be sufficient to gain private sector acceptance.

THE ADVANCED GASIFIER

The advanced gasifier module uses M. W. Kellogg's transport reactor technology (Figure 1). The transport reactor was selected for the gas generator due to its flexibility to produce gas and particulates under either pressurized combustion (oxidizing) or gasification (reducing) conditions for parametric testing of PCD's over a wide range of operating temperatures, gas velocities, and particulate loadings.[2] The transport reactor is sized to process 1814 kg/hr (2 tons/hr) of coal to deliver .472 actual m^3/s (1,000 acfm) of particulate laden gas to the PCD inlet over the temperature range of 538 to 982°C (1,000-1,800°F) at 1269-1951 kPa (184-283 psia). Two PCD's will be tested on the transport reactor, at alternate times. Short term (500 hour) parametric tests will be conducted using the transport reactor.

THE ADVANCED PRESSURIZED FLUIDIZED-BED COMBUSTION SYSTEM (PFBC)

The PFBC uses Foster Wheeler's second-generation PFBC technology (Figure 2).[3] The advanced PFBC system consists of a pressurized 1172 kPa (170 psia) carbonizer at 871-982°C (1600-1800°F) to generate .708-.802 actual m^3/s (1500-1700 acfm) of low-Btu fuel gas and a circulating pressurized fluidized-bed combustor (CPFBC), operating at 1034 kPa (150 psia) and 871°C (1600°F), which generates 2.93 actual m^3/s (6,200 acfm) of combustion gas. The coal feed rate to the carbonizer will be 2495 kg/hr (2.75 tons/hr). A Ca/S molar ratio of 1.75 is required to capture 90 percent of the sulfur in the carbonizer/CPFBC. Char which is not converted to gas in the carbonizer is transferred hot to the CPFBC. The gases exiting from the carbonizer and the CPFBC will each be filtered hot in separate PCD's to remove particulates prior to entering the topping combustor.

THE TOPPING COMBUSTOR/GAS TURBINE

A topping combustor will be used to raise the inlet temperature of the gas turbine to 1288°C (2350°F) (Figure 3). The higher turbine inlet temperature will raise the net plant efficiency of advanced PFBC systems to 45 percent, while maintaining low levels of NOx. To withstand the expected severe conditions in the topping combustor application, a Multi-Annular Swirl Burner developed by Westinghouse has been chosen to combust the gases from the carbonizer and increase the temperature of the CPFBC flue gases, consistent with turbine inlet temperatures offered on advanced commercial high-efficiency turbines.[4] At the PSDF, however, the topping combustor flue gas must then be cooled to 1077°C (1970°F) in order to meet the temperature limitation of the small, standard gas turbine (Allison Model 501-KM) which will be used to power both the air compressor and an electric generator to produce about 4 MW of electric power.

PARTICLE FILTERS

At the PSDF, PCD's will be tested at temperatures, pressures, and other gas conditions characteristic of a number of gasifiers and PFBC's.[5] The critical issues include integration of the PCD's into the advanced power systems, on-line cleaning, chemical and thermal degradation of components, fatigue and other modes of physical failure, blinding, collection efficiency as a function of particle size, and scale-up issues.

The hot gases coming off the transport reactor, carbonizer, and CPFBC will be cleaned by different PCD's. The particulate control devices to clean gases from both the Foster Wheeler Carbonizer and Kellogg's transport reactor are the same size, to allow for the possibility of interchanging these three PCD's. One larger PCD will be tested on the combustion gases from the CPFBC.

A total of four PCD's from three developers have been selected for initial testing at the PSDF. Each of the PCD's is expected to maintain outlet particulate loadings of less than 20 ppmw with no more than 1 percent of the particles larger than 10 microns and no more than 10 percent of the particles larger than 5 microns to protect the gas turbine from erosion. The baseline pressure drop of the PCD's is expected to be less than 24.9 kPa (100 inches of water) with the maximum pressure drop less than 49.8 kPa (200 inches of water). The commercial version of the PCD's should have a temperature drop of less than 5.6°C (10°F) but in the PSDF a target of 33°C (60°F) has been set because of the smaller size of the PCD's.

The two PCD's which will be tested initially on the transport reactor are described below. They will operate at .472 actual m^3/s (1000 acfm) gas flow rates at 538-982°C (1000-1800°F), 1379-2068 kPa (200-300 psia), and 4000-16000 ppmw particle loading under both oxidizing and reducing conditions.

For one of the transport reactor/carbonizer filters, Westinghouse will use a vessel which can be fitted with ceramic candles, cross flow filters, CeraMem ceramic filters, or 3M ceramic bag filters in a tiered arrangement (Figure 4). The filter vessel will be a refractory-lined, coded, pressure vessel. The filters will be individual filter elements attached to a common plenum and discharge pipe to form clusters. Clusters of filters will be supported from a common high-alloy, uncooled, tubesheet. Each plenum of the filter will be cleaned from a single pulse nozzle. The number and size of the filters required will vary. For instance, 20 CeraMem filters or 80 candle filters would be needed.

The other filter on the transport reactor will be the Combustion Power Company granular-bed filter (Figure 5). The gas is introduced into the center of a downward moving-bed of granules, 6 mm spheres mostly made of aluminum oxide and mullite, which serve as the filter media to remove the particles from the gas. The gas reverses direction and moves counter current to the direction of the filter media to leave the pressure vessel. Clean media is constantly introduced from the top of the vessel. The particulate-containing media is removed from the bottom of the filter vessel and pneumatically conveyed and cleaned in a lift pipe. At the top of the lift pipe the particulate and clean media are separated in a disengagement vessel and the clean media is returned to the filter vessel. The transport gas and dust are cooled in a regenerative heat exchanger and the dust is removed in a baghouse. The transport gas is cooled in a water cooled heat exchanger and a mist eliminator, and then a boost blower is used to overcome the pressure drop in the system and the gas is reheated in the regenerative heat exchanger and recycled to the lift pipe.

Initial testing of a filter manufactured by Industrial Filter and Pump (IF&P) will be done on the PFBC carbonizer. The IF&P PCD will operate at .708-.802 actual m^3/s (1500 - 1700 acfm) gas flow rates at 871-982°C (1600 - 1800°F), 1172 kPa (170 psia), and 11,000 ppmw particle loading. The IF&P filters are ceramic candles made of low density aluminosilicate fiber and silica with an alumina binder and have densified monolithic end caps and flanges. The tubesheet is made of the same densified material. The 152.4 cm (60 inch) diameter, refractory-lined filter vessel will contain 78 candles arranged in 6 groups of 13 each for pulse cleaning. Individual jet pulse nozzles are provided to each candle. An Enhancer™ consisting of an orifice-type device at the outlet of the candle increases the pulse intensity and also serves as a fail-safe plug in case of a candle failure.[6]

A larger Westinghouse filter will be tested on the PFBC combustor.[7] The Westinghouse PCD will operate at 2.93 actual m^3/s (6200 acfm) gas flow rate at 871°C (1600°F), 1034 kPa (150 psia), and 15,000 ppmw particle loading. This filter will contain six clusters of ceramic candles in a 3.11 m (10.2 foot) outside diameter, refractory-lined pressure vessel. Two clusters of filters are attached to a common plenum and discharge pipe and each cluster is cleaned from a single pulse nozzle source. The three plenums of filter clusters are arranged vertically in the filter vessel. The cluster concept allows replacement of individual filters and provides a modular approach to scale-up.

THE FUEL CELL

Plans are being made to eventually integrate a Fuel Cell module with the transport gasifier. Molten carbonate fuel cell and solid-oxide fuel cell concepts are under consideration for use at the PSDF. The capacity of the fuel cell to be tested initially is 100 kW. This will be accomplished by utilizing EPRI's 100 kW Fuel Cell Test Skid at the facility. Provision has been made in the site layout of the PSDF to phase in a multi-MW fuel cell module with commercial stacks utilizing more than 80 percent of gases from the transport gasifier. At a multi-MW scale, testing can begin to address integration issues and overall plant performance for integrated gasification/fuel cell systems.

CURRENT STATUS OF THE PSDF

Environmental approvals for the PSDF were received in August 1993. Site preparation was completed in December 1993. All of the technologies have been selected and contracts have been signed. Detailed design is nearing completion and equipment fabrication is underway. Construction of the process tower began in mid November 1994.

SCHEDULE

The project will be completed in four Phases. Phase I, Conceptual Design, was completed in June 1992. Phase 2, Detailed Design, will be completed in the first quarter of 1995. Phase 3, Construction, began with site clearing in September 1993 after National Environmental Policy Act (NEPA) approval was obtained for the site. Construction of the transport reactor is scheduled for completion in September 1995 and for the APFBC in March of 1996. Phase 4, Operation, will begin as soon as shakedown and commissioning of each part of the facility is completed and will extend until December 1997 under the present agreement. A detailed test plan is being developed for the first operating phase. It is expected that additional operating phases will be funded, with the addition and/or substitution of other equipment and processes.

SUMMARY

The PSDF design incorporates advanced power system technology modules into integrated process paths. The size of the PSDF allows key component and system integration issues to be addressed at a reasonable engineering scale. Besides individual components testing, this design scheme allows testing and demonstration of integrated, advanced coal-based power generating systems. PCD's and components may be tested under long-term, realistic IGCC and advanced PFBC conditions.

Testing and development of components and systems under long-term, realistic conditions, are critical to the development of cleaner, more efficient, coal-fired power generating systems. The Power Systems Development Facility will play an important role in achieving these tests to support scale-up to demonstration plant sizes. This should have a significant impact on the design and cost of demonstration plants for the development of new technology in the future.

The result of this project will be a reduction or stabilization in the cost-of-electricity and a reduction in environmental emissions for new coal-based power plants.

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FIGURE 1. TRANSPORT REACTOR

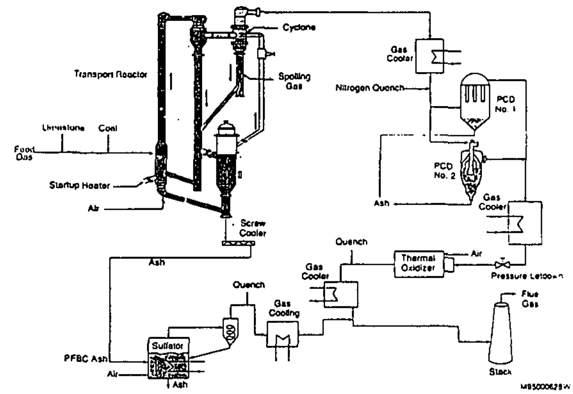

FIGURE 2. SECOND GENERATION PRESSURIZED FLUIDIZED BED COMBUSTION

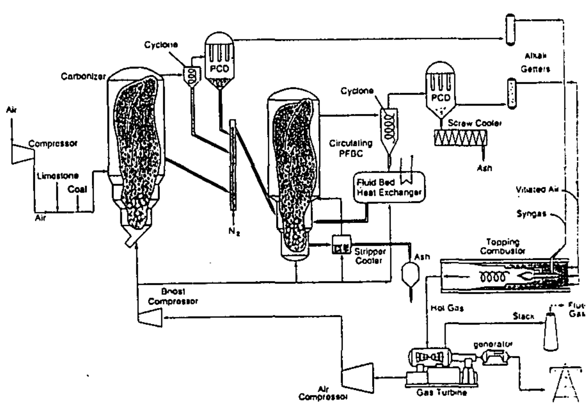

FIGURE 3. TOPPING COMBUSTOR

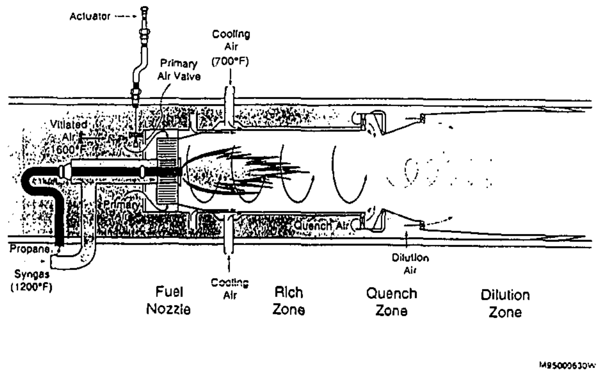

FIGURE 4. CANDLE FILTER

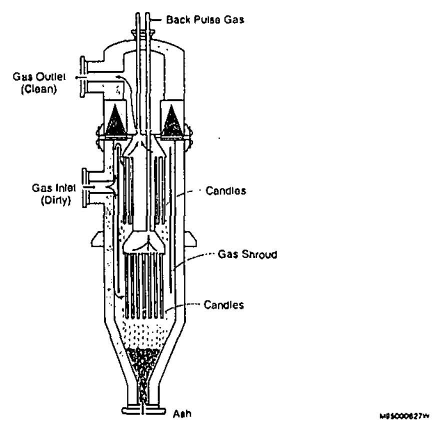

FIGURE 5. GRANULAR BED FILTER